



ELSEVIER

Agricultural and Forest Meteorology 96 (1999) 165–179

AGRICULTURAL  
AND  
FOREST  
METEOROLOGY

www.elsevier.com/locate/agrformet

## Measured sap flow and simulated transpiration from a poplar stand in Flanders (Belgium)

L. Meiresonne<sup>a,\*</sup>, N. Nadezhdin<sup>b</sup>, J. Cermak<sup>b</sup>,  
J. Van Slycken<sup>a</sup>, R. Ceulemans<sup>c</sup>

<sup>a</sup>*Institute for Forestry and Game Management (IBW), Ministry of the Flemish Community,  
Gaverstraat 4 B-9500 Geraardsbergen, Belgium*

<sup>b</sup>*Institute of Forest Ecology, Faculty of Forestry and Wood Technology,*

*Mendel University of Agriculture and Forestry, Zemedelska 3, CS-61300 Brno, Czech Republic*

<sup>c</sup>*Department of Biology, University of Antwerpen (UIA), Universiteitsplein 1 B-2610 Wilrijk, Belgium*

Received 15 June 1998; received in revised form 25 June 1999; accepted 1 July 1999

### Abstract

This study reports on the transpiration by a hybrid poplar (*Populus trichocarpa* × *P. deltoides*) plantation in East Flanders during 1997. Transpiration was measured by sap flow techniques on individual trees and scaled to the stand level, and was simulated by the WAVE water balance model. Relatively high transpiration values by the poplar stand were found during the growing season, with maximum and mean daily transpiration of 5 and 1.9 mm per day, respectively. The seasonal (1 April–31 October) total transpiration amounted to 320 mm, representing roughly 70% of the potential evapotranspiration over this period. However, this transpiration represented only about three-fourths of the incoming precipitation. Reasonable agreement was found between measured and simulated stand transpiration. The difference between cumulated precipitation and cumulated actual transpiration closely mimicked the course of the water table. Suggestions for further improvements to the WAVE model have been made and discussed. © 1999 Published by Elsevier Science B.V. All rights reserved.

**Keywords:** Poplar; Transpiration rate; Water balance; Sap flow

### 1. Introduction

Trees have a large effect on the hydrological cycle. The water use, or evaporative loss, of vegetation consists of two components, i.e., active transpiration

(from the soil through live plants) and interception (direct evaporation from live and dead plants and the soil surface). For most stands of broad-leaved trees, transpiration is the major component of water use. In a review of 92 catchment experiments world-wide, Bosch and Hewlett (1982) showed an average reduction of water yield of approximately 25 mm per year for every 10% of a catchment under mature deciduous trees, as compared with grass or pioneer vegetation;

\* Corresponding author. Tel.: +32-54-437-118/11; fax: +32-54-410-896

E-mail address: linda.meiresonne@lin.vlaanderen (L. Meiresonne)

the equivalent figure for coniferous forests was 40 mm per year. Although there has been less work done on the stand water use by broad-leaved trees than by coniferous trees, a number of values of annual stand transpiration can be found in the literature for deciduous species. For example, the yearly stand transpiration of an ash forest on chalk soils in southern Britain was 372 mm, which slightly exceeded that from a beech forest — 355 mm (Roberts and Rosier, 1994). On clay soils, the average annual transpiration of ash for the same years was 327 mm (Harding et al., 1992). These annual values are in agreement with the values for deciduous trees listed in Hall and Roberts (1990). They demonstrate that the total water use of beech and ash forests on chalk and clay formations in southern Britain was less than it was for grass.

Hybrid poplar (*Populus* spp.) is an excellent tree species in rotation cycles of 15–20 years, because of its superior growth vigour and high wood production. It has been widely planted and cultivated in various countries (Anonymous, 1996) and is a major wood source in western Europe. Poplar plantations are also important in several parts of Flanders (Belgium). Poplars prefer moist to wet soils for optimal growth and production levels. But the possibly high water consumption of this fast growing tree species has led to concerns that large plantations may affect regional water table levels, or reduce aquifer recharge and river flows. There have been few studies on stand transpiration and stand water balance of poplar under longer rotations. Van Slycken and Vereecken (1990) used a water balance model to relate yield to water availability in an attempt to understand the variability in growth at a 2 ha hybrid poplar plantation in Belgium. Their model was used to predict water supply through capillary rise from the groundwater table. Valadon and Diot (1996) found few references to poplar water cycle in their bibliographic review. For poplar under shorter rotation cycles, a detailed study on a four-year-old hybrid poplar (*Populus trichocarpa* × *P. deltoides*) stand in the Pacific Northwest (USA) yielded a maximum stand transpiration rate of 4.8 mm per day (Hinckley et al., 1994). However, measurements in this study were carried out only over a short time period and no modelling was performed; consequently, no longer-term data was presented. Similarly, for a two- and five-year-old irrigated poplar coppice stand, transpiration rates of 4.4 to 4.8 mm per day have

been reported (Hansen, 1988). A comprehensive synoptic review on poplar stand transpiration has been given in Table 1. Values cited and mentioned above have been included in this table.

The main objectives of this study were (1) to quantify the transpiration of a fast-growing 13-year-old monoclonal poplar stand in East Flanders (Belgium) using two different approaches, (2) to compare the stand transpiration values scaled up from sap flow measurements on individual representative trees with those simulated by a water balance model, and (3) to relate the transpiration from the poplar stand to the potential evapotranspiration and the incoming precipitation.

## 2. Materials and methods

### 2.1. Experimental site and stand description

The experimental poplar stand is located at Balegem (50°55'N, 3°47'E), in the sandy loam region of the province of East Flanders, Belgium, at a height of 45 m above sea level. The site is a former meadow with orchard of about 1.5 ha and the relief is flat. The soil is moderately gleyic loamy, with a degraded texture-B horizon, the texture becoming coarser with depth and with an Ap-horizon of 30 cm thick. The Belgian soil survey classifies the soil as an Adc(z)<sub>30</sub>. The FAO soil taxonomic classification refers to the soil as a Glossaqualf. Mean annual and growing season totals (1 April–31 October) of precipitation and evaporation at the site are given in Table 2.

In 1984, approximately 1 ha was planted with two-year-old sets of the poplar clone *Populus trichocarpa* × *P. deltoides* cv. Beaupré, while the rest of the area was planted with the clone *Populus trichocarpa* × *P. deltoides* cv. Boelare. The spacing in the entire plantation was approximately 7 m × 7.5 m. In the winter of 1996–1997, the average height of the Beaupré trees was 31.6 m, the stand basal area 25.1 m<sup>2</sup> ha<sup>-1</sup> and the average stem volume 1.77 m<sup>3</sup>. With a mean circumference of 132 cm at breast height at the age of 13 years, an average yearly circumference increment of 10.2 cm per year was obtained. The frequency distribution of the diameter at breast height is illustrated by Fig. 1.

Table 1  
Comparative literature survey of stand transpiration of poplar (*Populus*)

Poplar ( <i>Populus</i> )	Location	Daily transpiration (mm/day)	Total growing season transpiration (mm/growing season)	Stand age (years)	Reference
<i>P. tristis</i>	Wisconsin State, USA	4.4–4.8	–	2 and 5	Hansen (1988)
<i>P. trichocarpa</i> × <i>P. deltoides</i>	Buckinghamshire and Avon, UK	1–8	–	3	Hall et al. (1998), Hall and Allen (1997)
<i>P. euramericana</i> , clone I-214	Northern Italy	–	158	4	Anselmi (1982)
<i>P. trichocarpa</i> × <i>P. deltoides</i>	Washington State, USA	3.6 (average), 4.8 (maximum)	430–550	4	Hinckley et al. (1994)
<i>P. deltoides</i>	Michigan State, USA	–	128	2	Liu et al. (1988)
			365	3	Liu and Dickmann (1992)
			603	6	
<i>P. trichocarpa</i> × <i>P. deltoides</i>	East Flanders, Belgium	1.9 (average), 5 (maximum)	320	13	Present study
<i>P. tremuloides</i>	Saskatchewan, Canada	5–6 (maximum)	400	70	Black et al. (1996)

Table 2

Precipitation ( $P$ ), potential evapotranspiration over grass ( $E_r$ ) and difference between precipitation and potential evapotranspiration ( $P - E_r$ ) at the experimental poplar site in Balegem (East Flanders, Belgium)<sup>a</sup>

Period	Precipitation during 1833–1975 (mm)	Potential evapotranspiration over grass during 1967–1986 (mm)	Difference between precipitation and potential evapotranspiration (mm)
During the year	750	548.7	+204.3
During the growing season	465	470.3	–5.3

<sup>a</sup>Long-term averages expressed on an annual basis, as well as over a growing season, are being represented (data modified after Dupriez and Sneyers, 1979; Gellens-Meulenberghs and Gellens, 1992).

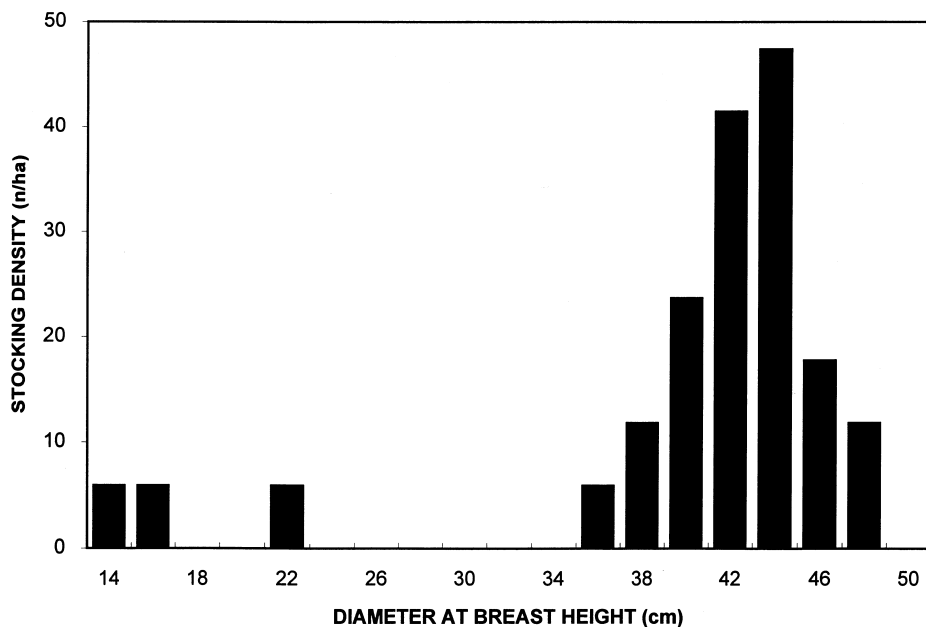


Fig. 1. Tree stocking density for all DBH (diameter at breast height) classes in the poplar stand in Balegem.

In the summer of 1997, five representative poplar trees of the clone *Populus trichocarpa* × *P. deltoides* cv. Beaupré were selected out of the very uniform plantation for the sap flow measurements. A small

poplar tree was also included in the experiment to illustrate the different behaviour of dominant and suppressed trees. Biometric data of the selected trees are given in Table 3.

Table 3

Biometric data of the sap flow sample trees

Tree No.	Diameter at breast height (cm)	Basal area (cm <sup>2</sup> )	Bark thickness (cm)	Crown radii: N, E, S, W (m)	Projected crown area (m <sup>2</sup> )
1	39.9	1253.4	1.1	3.9, 4.6, 3.4, 4.3	51.8
2	44.2	1537.5	1.1	4.3, 6.3, 4.2, 4.0	69.4
4	38.5	1165.1	1.1	4.2, 3.4, 3.4, 5.3	52.2
5	42.0	1386.6	0.9	4.0, 4.0, 3.5, 4.7	51.5
7	47.1	1743.1	1.1	4.8, 4.1, 7.0, 3.5	73.9
8	16.4	211.1	0.8	0.8, 1.0, 1.7, 4.2	11.6

## 2.2. Monitoring of the water balance in the poplar stand

Climatological conditions at 2 m height were continuously measured by an automatic weather station (Didcot Instrument Co. Ltd., Abingdon, UK), installed in a nearby meadow. A data logger (Campbell Scientific CR10, Shepshed, UK) permanently monitored precipitation (tipping bucket Didcot DRG-51), wind speed (Didcot DWR-205), wind direction (Didcot DWD-105), photosynthetic active radiation (Didcot DRP-1), air temperature and relative humidity (wet and dry psychrometer Didcot DTS-5) and incoming short-wave radiation (tube solarimeter, Delta-T-Devices, TSL, Burwell, UK).

A second weather station (Didcot) in between the trees recorded, besides air temperature and relative humidity (Didcot DTS-5), short-wave radiation (tube solarimeter, Delta-T-Devices, TSL, Burwell, UK) and air pressure. In order to determine the interception, net precipitation was measured by flowmeters (Didcot DFM-250). They recorded the throughfall collected by plastic gutters (3 m<sup>2</sup> surface area) in between the trees and the stemflow collected by spirals along the stem of two representative trees. The fluctuations of the groundwater table (Didcot DWL-10) were also followed to a depth of 4.4 m. Two different methods were used to measure soil moisture. TDR sensors were installed horizontally up to a depth of 3 m, at intervals of 25 cm, for the soil moisture content and measured by a cable tester (Tectronix 1502B, Redmond, USA). Tensiometers (Delta-T-Devices, SWT6, Burwell, UK) measured the soil water tension to a depth of 1.5 m. All data were measured every 30 s and recorded as means over 1 h intervals. During the period of the sap flow campaign (9 August–2 September 1997), the means were calculated over 15 min intervals. The TDR sensors were measured manually twice a week.

If on particular days precipitation data were missing, because of failure and repair of the tipping bucket, data were supplied from the Royal Meteorological Institute of Belgium, which has weather stations near the experimental plot: Melle, at 9 km distance, which provided hourly data, and Munte, at 4 km distance, which supplied daily data.

In autumn of each year, leaves were collected in 10 baskets with a total surface of 2.8 m<sup>2</sup> and oven dried.

With a previously determined specific leaf area, the maximum leaf area index ( $L_m$ ) was determined.

The ratio between the solar radiation inside ( $R_i$ ) and outside the stand ( $R_o$ ) reflects the plant area index ( $P$ ). The evolution of the leaf area index ( $L$ ) during the growing season was derived from this ratio, assuming that winter values (subscript w) of the ratio correspond to the skeleton area index,  $S$  ( $L = P - S$ ):

$$L_t = L_m \left[ \left( \frac{R_i}{R_o} \right)_t - \left( \frac{R_i}{R_o} \right)_w \right] \quad (1)$$

where  $L_t$  is the leaf area index at time  $t$ .

The growth of five model trees was followed by microdendrometers, on a weekly basis.

## 2.3. Simulation of the water balance

For the simulation of the water balance, the WAVE (Water and Agrochemicals in soil, crop and Vadose Environment) model has been used (Vanclooster et al., 1994). This model describes the transport and transformations of matter and energy in the soil, crop and vadose environment. The WAVE model consists of different modules, and the water transport module is a revised version of the SWATRER model (Feddes et al., 1978). It describes the one-dimensional water transport in the soil using the equation of Richards (1931), which is based on the soil hydraulic properties. These include soil moisture retention, described by the power function model of van Genuchten (van Genuchten, 1980; van Genuchten and Nielsen, 1985) and the hydraulic conductivity relationship, for which the Gardner (1958) model performed well in Belgian conditions (Vereecken et al., 1990).

The soil profile is divided into a number of compartments, and the total time period into discrete time increments of unequal lengths (time steps smaller than 1 day), for the numerical calculation of the soil water fluxes. The conductivity and the differential moisture capacity are linearised.

The maximum potential crop evapotranspiration ( $E_c$ ) is required as input, and is calculated by multiplying the potential evapotranspiration of a reference surface ( $E_r$ ) with a crop coefficient ( $K_c$ ).  $E_r$  is calculated according to the Penman–Monteith equation (Monteith, 1965) for a standard stand of short cut grass, with roughness length 0.0015 m, zero plane displacement 0.08 m and canopy resistance

$70 \text{ s m}^{-1}$ , using the AWSET (Hess, 1995) program for automatic weather stations. The potential transpiration ( $T_p$ ) and evaporation ( $E_s$ ) are obtained by splitting  $E_c$ , using the leaf area index as splitting factor.

$$E_s = e^{-0.6L} E_c \quad (2)$$

$$T_p = E_c - E_s - I \quad (3)$$

where  $I$  is the interception (mm).

The actual transpiration is the integral of the root water uptake over the profile. This is the relative maximum root water uptake as a function of depth, multiplied by a sink term. This term expresses the effect of the current pressure head on the potential root water uptake. The actual transpiration is limited by, and can never be greater than, the potential transpiration. While the water transport module of WAVE was originally developed for agricultural crops, it has been calibrated for forest conditions, too (Hubrechts et al., 1997). In particular, the crop coefficient,  $K_c$ , the sink term and the relative root distribution are subjected to calibration. The soil moisture profile, as determined by the TDR sensors and the tensiometers, is used as calibration parameter.

As input, the program requires some general profile information, daily climatological data (precipitation, reference potential evapotranspiration and interception capacity), soil hydraulic properties (soil moisture retention curve and hydraulic conductivity relationship), the course of the groundwater table, if present, and some crop-specific information ( $L_i$ ,  $K_c$ , relative root distribution).

The model produces daily and cumulative values of evaporation, transpiration and evapotranspiration, the integrated upward and downward water fluxes and change of water storage at the bottom of the profile and at the bottom of the upper layer, the moisture content as well as the pressure head and root water extraction for each layer.

#### 2.4. Measurement and evaluation of sap flow rates

Sap flow was measured in all experimental trees using the heat field deformation method with linear radial heating and a combined sensor (Nadezhdina and Cermak, 1998). The combined sensor consisted of a

heater (insulated resistance wire) and two or three pairs of thermocouples situated around the heater. Both the heater and the thermocouples were incorporated into stainless steel hypodermic needles, with an outer diameter of 1.2 mm. For the routine measurements of sap flow (primarily focused on diurnal dynamics of flow), standard sensors were inserted into a known depth below the cambium. Additionally, a series of special sensors were applied to measure the sap flow at different depths. Sap flow rate was measured at six depths below the cambium within the sapwood, in order to get the radial pattern of flow and to specify the best position of the standard sensors. Each needle of such a sensor contained six thermocouples. The thermocouples were arranged in the different sensors at equal distances of 10 or 15 mm; thus, the sensors were covering depths of 50 and 75 mm below the cambium. The temperature differences were measured every minute and recorded as means over 15 min intervals (occasionally during intensive studies over 1 min intervals) by a datalogger (Unilog & Environmental Measuring Systems, Inc., type EMS-12, Brno, Czech Republic).

The non-homogeneous flow in the different sapwood depths was integrated over the whole sapwood area in order to get data for entire stems. Transpiration of the entire plantation stand area unit was scaled up from sap flow data for individual trees, based on the stand inventory. The scaling-up procedure has been described in detail by Cermak et al. (1997, 1998) and by Cermak and Kucera (1987, 1990), but in brief the procedure is as follows. The mean daily sap flow rate in individual sample trees was related to the basal area and, alternatively, to the projected crown area of the sample trees. Transpiration of the mean trees for each DBH class was derived from the corresponding regressions. Stand transpiration was obtained by multiplying values for the mean trees with the corresponding number of trees in each class, and summing.

All measurements at 15 min intervals were integrated to daily transpiration rates,  $T_d$ , over the measuring period (8 August–3 September 1997). By relating these data to potential evapotranspiration,  $E_c$ , it was possible to calculate the transpiration for the whole growing season  $T_s$ . However, because of the evolution of the leaf area during the growing season, a correction factor was used, the ratio between the leaf

area index for a particular short period ( $L_t$ ) and the maximum leaf area index ( $L_m$ ). This full foliage leaf area index was reached in 1997, from 5 June to 7 September.

$$T_t = T_s \left( \frac{L_t}{L_m} \right), \quad (4)$$

where  $T_t$  is the corrected transpiration at any time  $t$ .

### 3. Results

#### 3.1. Upscaling the transpiration data from trees to stands

The tree stems were very symmetrical, which corresponded to minimum differences in sap flow between measuring points. The radial pattern of sap flow, discussed elsewhere (Cermak and Nadezhdina, 1998), indicated that the whole sapwood area was conducting, although not at the same rate all over the area; maximum flow occurred around the middle part of sapwood. Both linear and curvilinear regressions for deriving transpiration of mean trees of each DBH class (Table 4) showed a very good fit. But the application of the curvilinear equation was taken as more reliable, especially for the smallest and largest trees at the stand, according to the experience on other experimental sites (Cermak et al., 1997). The basal area was taken as a more suitable independent variable, because it is easier to measure at the stand level. Although the crown projected area also showed good relationships in the sample trees, both independent variables gave similar results. A relatively low number of trees seemed sufficient for upscaling, because the plantation was very homogenous. The small tree was an exception, but did not deviate from the general relationship and helped anchor the scaling curves close to the origin.

#### 3.2. Comparison of the measured and the modelled transpiration data

The totals over the whole period from 9 August to 3 September showed good agreement between the modelled and the measured transpiration, i.e., 141 and 149 mm, respectively. However, consideration of the individual daily totals showed that on about a quarter of the days, the model significantly under- or over-estimated the transpiration scaled up from the sap flow measurements (Fig. 2). A more detailed analysis of the diurnal courses was necessary.

On days with the best fit between the modelled and the measured transpiration rates (period A in Fig. 2), there was only 2–10% difference between both approaches. These were days without precipitation. The high and variable radiation showed daily totals of around 22 MJ m<sup>-2</sup> per day, but actual peak values persisted only for short time periods, of the order of minutes. The vapour pressure deficit (VPD) was medium to high, with daytime maximum about 12 hPa, night-time around zero. On these days, the sap flow reached highest daytime peak values and medium levels of night-time flows, i.e., about 10% of the daytime values (Fig. 3).

Situations where the model showed higher daily values of transpiration than those measured (period B, 9–10 August, in Fig. 2), were also days without precipitation. However, there was an almost cloudless sky. The daily totals of radiation were above 24 MJ m<sup>-2</sup> per day, and actual peak values persisted for rather long periods of time, of the order of hours. The VPD was high, with daytime maximum VPD of about 18 hPa, night-time VPD between 2 and 4 hPa. The daytime values of the sap flow were lower than in the previous case. Moreover, in this period the highest night-time flow rates were reached, up to 15% of daytime values, and these were found to be highly sensitive to VPD (Fig. 4). The diurnal variation of the

Table 4  
Linear and non-linear equations relating the mean daily transpiration ( $T_d$ ) of the sample trees to their biometric parameters

Independent variable	Equation	$r^2$
Basal area ( $X_1$ )	$T_d = 0.12 X_1$	0.98
	$T_d = 315 \exp(-3.4 \exp(-0.00124 X_1))$	0.98
Projected crown area ( $X_2$ )	$T_d = 2.96 X_2$	0.98
	$T_d = 315 \exp(-3.5 \exp(-0.0306 X_2))$	0.98

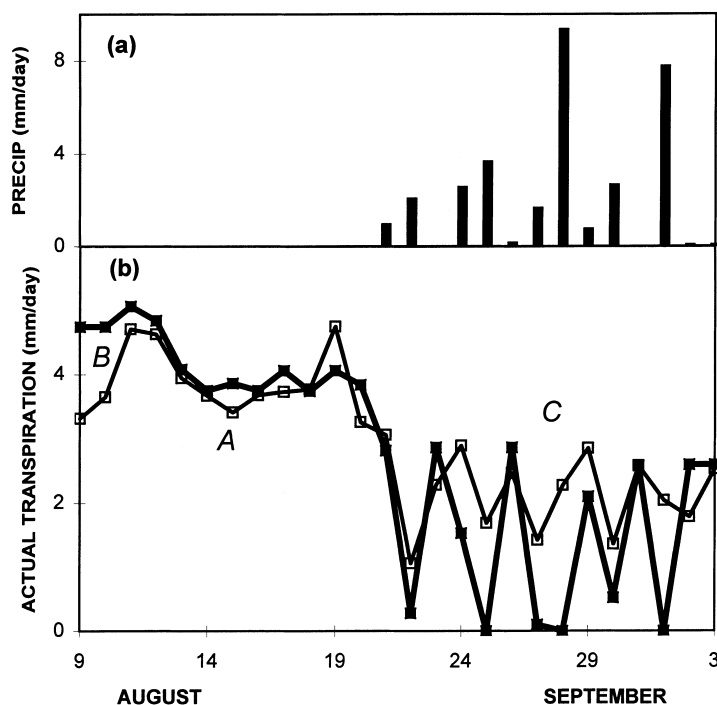


Fig. 2. (a) Precipitation during the intensive study period (sap flow measurement campaign) of 9 August to 3 September 1997. Three specific periods (represented by A, B and C) were analysed in more detail as discussed in the text; (b) Daily totals of actual stand transpiration, as measured by the sap flow method (empty squares, thin line) and as simulated by the WAVE model (full squares, heavy line).

sap flow rates is consistent with stomatal closure during the midday hours, in response to water stress. The model does not reproduce such an effect. On 11 August, sap flow did reach higher levels, because VPD values were highest on 11 August in comparison with most other days, and also reached their maximum in late afternoon, when radiation already dropped (Figs. 2 and 4).

The model yielded lower values of daily transpiration than the measured ones (i.e., underestimated the measured transpiration) on days with precipitation events, e.g. period C in Fig. 2. However, the effect of the rain on the modelled transpiration rates was dependent on the amount and timing of the precipitation. When rainfall exceeded 1 mm, the model deviated from the measured transpiration when the rain did not fall within the period during which transpiration occurred. This clearly happened on 24 August (with most of the rainfall at night), on 28 August (with much of the rainfall in the morning), and on 1 September (with high rainfall during evening and

at night). On these dates, the model predicted zero transpiration, although the sap flow measurements showed a quite high transpiration level (Fig. 5). However, when the rainfall came from a short, but heavy shower (<1 mm) during daytime with a persisting evaporational demand, the simulated transpiration was close to the measurements: 26 and 29 August are good examples of this. Furthermore, on days with rather high precipitation (>1 mm; e.g., on 22 and 30 August) spread over a major part of the day with low radiation and evaporation demand, the model also satisfactorily simulated the stand transpiration. Typically, these days were also characterised by low VPDs (around 3 hPa during daytime and reaching zero during the night), as well as by low and variable incoming radiation levels, i.e., daily totals of global radiation ( $R_g$ ) were equal to or lower than  $12 \text{ MJ m}^{-2}$  per day. On these days, sap flow rates were also low, decreased, of course, during rainy events, and remained rather low for some time after the rainy period. The nighttime values of sap flow rates were lower than in both



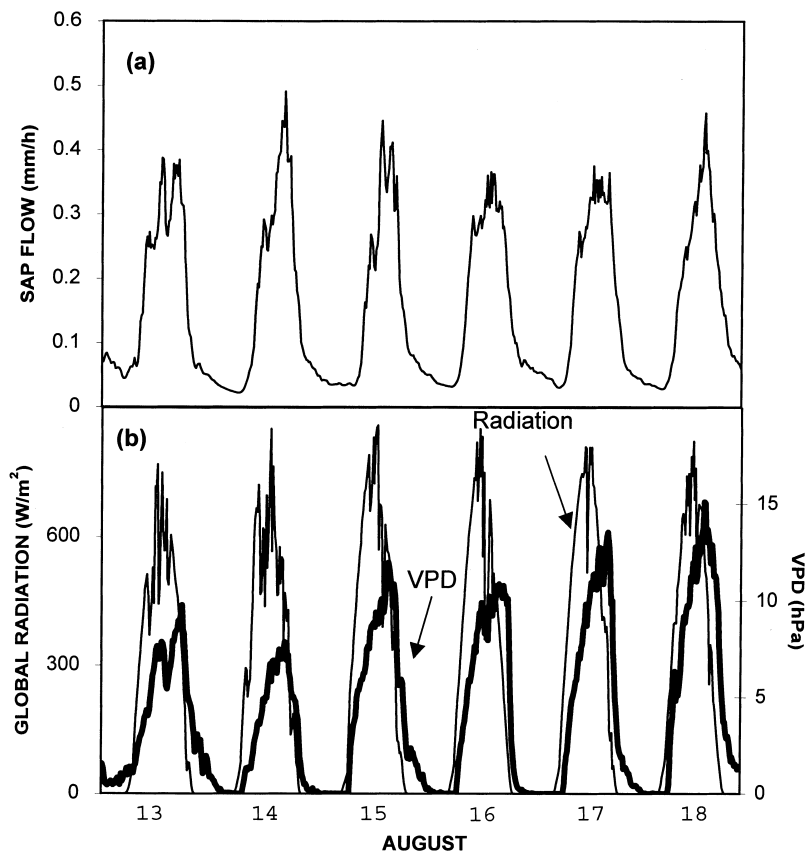


Fig. 3. (a) Typical diurnal course of sap flow rate, (b) incoming global radiation and vapour pressure deficit (VPD), as observed on selected days with a good correlation between measured (by sap flow method) and simulated (by the WAVE model) transpiration rates during period A with no precipitation.

previous situations, but they remained rather high (about 12% of maximum sap flow rates) when compared with the daytime values (Fig. 5).

### 3.3. Temporal scaling using $E_c$ and leaf area index data

The daily transpiration, as measured by the sap flow technique,  $T_d$ , showed a good correlation with potential evapotranspiration,  $E_c$  (Fig. 6). This allowed the application of the regression equation so that data could be extrapolated over a longer period of time outside the study period.

$$T_d = E_c 0.86 \quad (5)$$

This coefficient produced daily transpiration estimates in good agreement with the simulation for the period

with fully developed leaf area index  $L_m$  (period II in Fig. 7(a)) and, when seasonal changes of leaf area index were taken into consideration, for the period of leaf growth (20 April–5 June, period I, Fig. 7(a)) and leaf fall (7 September–7 October, period III, Fig. 7(a)).

When the growing season was considered from 1 April to 31 October (Fig. 7(b)), the seasonal total of  $E_c$  reached 508 mm. The actual stand transpiration (scaled up from the measured sap flow rates) reached 329 mm (with a maximum of 4.91 mm per day), which was very close to the value of 311 mm simulated by the model (with a maximum of 5.06 mm per day). So, the total cumulative transpiration of the poplar stand represented 65% (measured), respectively 61% (modelled) of  $E_c$ . When the growing season was restricted to the active period during which transpiration could really occur (i.e. with  $L > 0$ , from

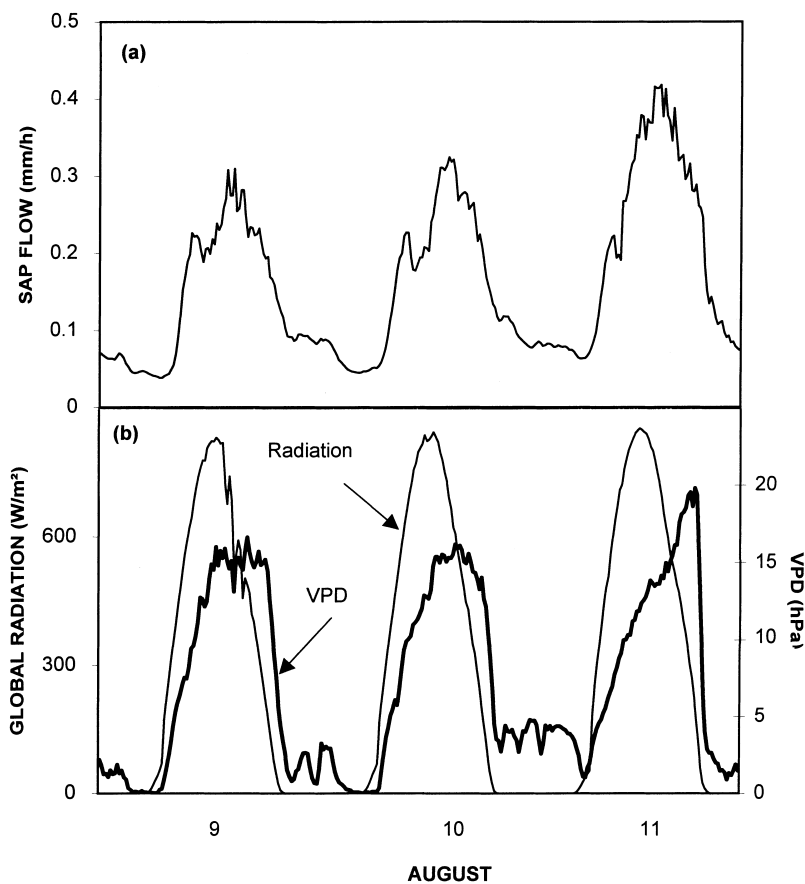


Fig. 4. (a) Typical diurnal course of sap flow rate, (b) incoming global radiation and vapour pressure deficit (VPD) as observed on days when the actual transpiration, as measured by the sap flow method, was overestimated by the WAVE model during period B with no precipitation.

19 April to 6 October 1997), the mean daily transpiration of the poplar stand was 1.92 mm per day, as obtained from the sap flow measurements, and 1.82 mm per day as a result of the modelling effort, for a mean  $E_c$  of 2.72 mm per day. The sound coherence between the simulated and the calculated transpiration course suggested that the slope of the regression (Fig. 6, Eq. (5)) was rather unaffected by phenological changes in the trees over the growing season.

Both stand transpiration and precipitation ( $P$ ) were reflected in the seasonal evolution of soil water content, with most pronounced changes in soil water content occurring in the upper soil layer (Fig. 8(a)). Furthermore, the calculated difference ( $D$ , in mm) between the cumulated precipitation and the cumulated transpiration,  $D = P - T_d$  also clearly reflected

the pronounced changes in the level of the groundwater table (see Fig. 8(b) and Fig. 9(a)). The regression between the difference of precipitation (430 mm) and transpiration (311 or 329 mm) cumulated over the period of fully developed foliage (i.e., 21 May–22 September) and the groundwater table level ( $H = 0.028 \times D - 4.75$ ) showed a good fit when transpiration data from the sap flow measurements were used ( $r^2 = 0.86$ ;  $SE = 0.332$ ). This regression was almost the same when simulated transpiration data from the model were used, although the fit was slightly lower, i.e.  $r^2 = 0.56$  (Fig. 9(b)).

#### 4. Discussion

This study reported seasonal transpiration by the monoclinal poplar stand of 320 mm, with a maximum

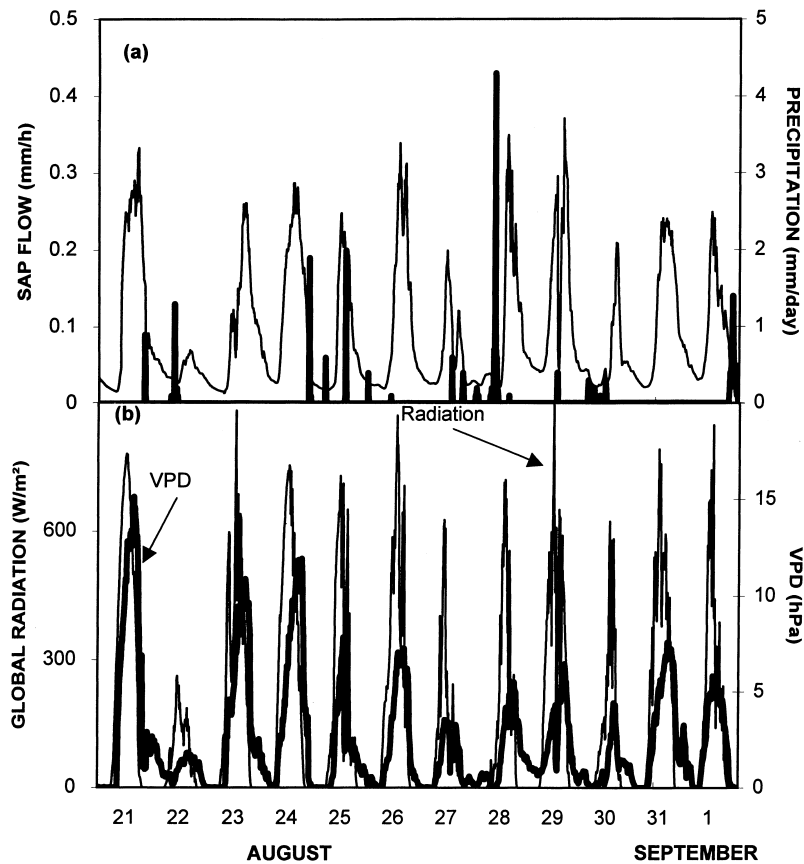


Fig. 5. (a) Typical diurnal course of sap flow rate and precipitation, (b) incoming global radiation and vapour pressure deficit (VPD) as observed on days when the actual transpiration, as measured by the sap flow method, was underestimated by the WAVE model during period C when rain occurred.

of 5 mm per day and daily mean of 1.9 mm per day. This was a considerable quantity of water when compared with other species in the region, such as Scots pine, where values of 1 mm per day were observed (Cermak et al., unpublished results). The stand transpiration values of this study are comparable to those available in the literature for many forests in Europe (Roberts, 1983). Stand transpiration of 430–550 mm were obtained in the Pacific Northwest when the measured transpiration rates of young interamerican hybrid poplars were extrapolated to a growing season of 120–150 days (Hinckley et al., 1994). On the other hand, values as low as 158 mm over 120 days of growing season were observed in Italy for *Populus × euramericana* (Anselmi, 1982). However, part of these differences might be explained

by stand age, as transpiration studies on *Populus deltoides* have shown (Liu et al., 1988; Liu and Dickmann, 1992). Black et al. (1996) found that the annual water use by a 70-year-old *Populus tremuloides* stand in northern Saskatchewan, Canada, was 400 mm and the maximum daily value almost 6 mm per day. For a coppiced poplar stand of the same clone (Beaupré), Hall et al. (1998) and Hall and Allen (1997) reported a variation in daily transpiration from 1–8 mm per day, depending on the supply of ground-water (Table 1).

Data from several studies reviewed by Hall and Roberts (1990) are characterised by annual transpiration totals substantially less than the potential transpiration for the site locations. However, transpiration totals for mature stands of several common European

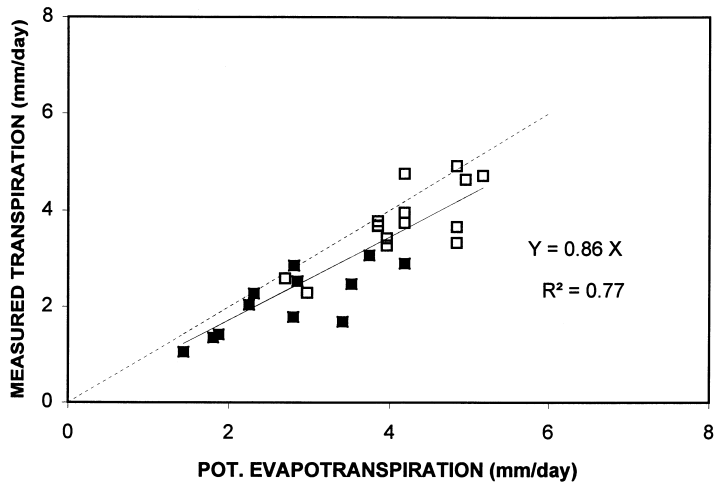


Fig. 6. Relation between actual transpiration ( $T_d$ ) of the poplar plantation, as measured by the sap flow method and scaled up to the stand level and potential evapotranspiration ( $E_c$ ). Values during a wet period: filled, black squares; values during a dry period: open, square symbols. The dotted line represents the 1 : 1 relationship.

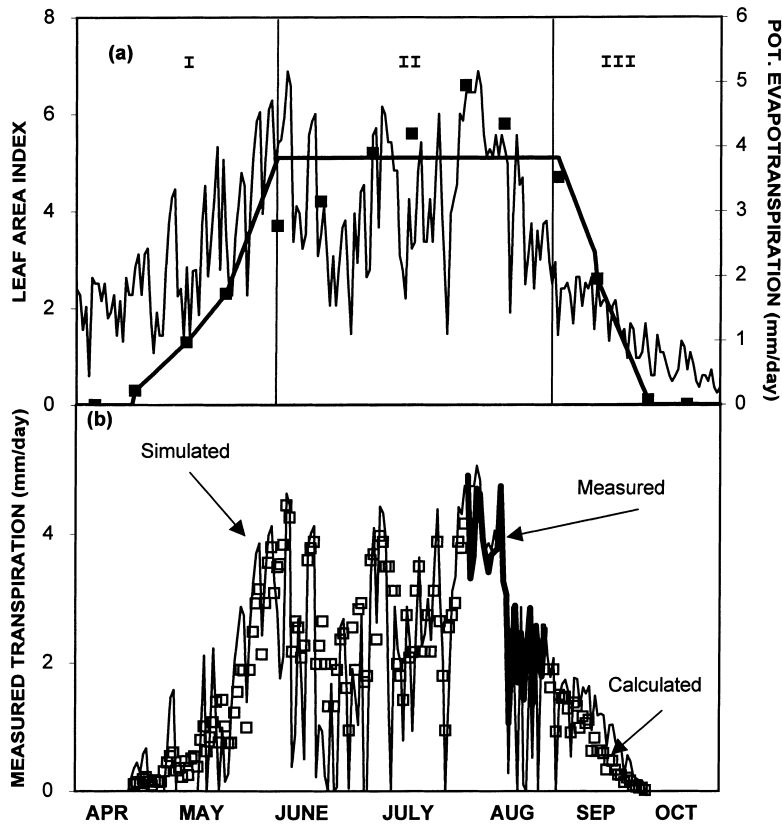


Fig. 7. (a) Seasonal course of potential evapotranspiration ( $E_c$ ) and leaf area index at the poplar plantation during the year 1997. I: leaf growth (spring), II: fully developed leaf area (summer), III: leaf fall (autumn). Only the evolution of the leaf area index from leaf flush in the spring until leaf fall in the autumn was applied for further calculations, supposing that LAI remained constant over the major part of the growing season (i.e., June–September). (b) Seasonal course of actual daily transpiration, either measured by the sap flow method (thick line), or simulated by the WAVE model (thin line). Values of actual transpiration calculated using  $E_c$  and corrected according to leaf area index development are marked by open squares.

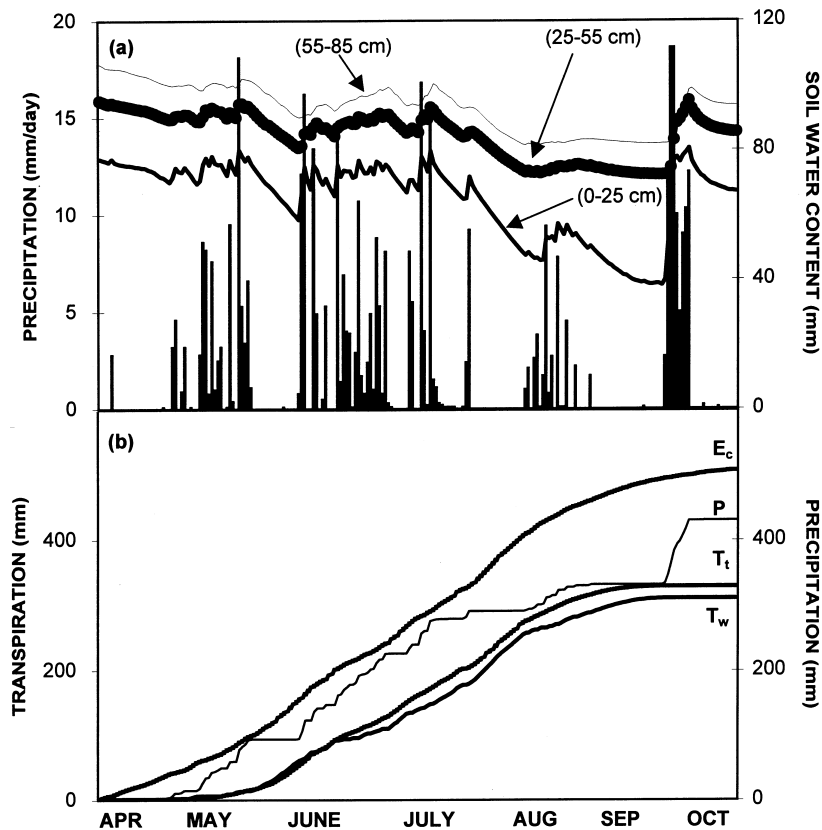


Fig. 8. (a) Seasonal course of soil water content at different depths (horizons) and daily precipitation at the poplar plantation during the year 1997. (b) Evolution of cumulative values of precipitation ( $P$ ), potential evapotranspiration ( $E_c$ ) and transpiration either measured by the sap flow method ( $T_t$ ) or simulated by the WAVE model ( $T_w$ ) for the poplar stand.

species, including poplar and willow, were unavailable (Harding et al., 1992). For the specific conditions of the present study in Balegem (Belgium), precipitation was also high enough, with the good water storage capacity of the loamy soil, probably to preserve the poplars from drought stress.

At present, few comparisons exist between scaled-up sap flow rates and simulated water balance. For determination of the transpiration of the monoclonal poplar stand, acceptable agreement was observed between the transpiration measured by the sap flow method on individual trees and scaled up to the stand level and the one simulated by the WAVE model. The model could be improved by introducing two-step calculation procedures. For example, on days of high evaporative demand, when the model overestimated transpiration, we could introduce a parameter to account for the reduction in stomatal conductance

in response to high evaporative demand caused by high values of radiation and VPD. Our results indicated that the threshold value of  $R_g$  is around  $24.8 \text{ MJ m}^{-2}$  per day, i.e. about 96% of the seasonal maxima, and that the threshold value of the simultaneously occurring VPD would be about 17 hPa, i.e. about 90% of the seasonal maxima. With regard to rainy days, when the model underestimated the stand transpiration, we suggest that not only the rainfall needs to be included in the model as an input variable for the calculation of the transpiration. As rainy events are followed by a period of interception, the diurnal distribution of the rainfall should also be included in the model, and this could be introduced either by a measurable parameter characterising the daytime period of leaf wetness, or by indicating the time of the rainy events, at least in terms of daytime (from early morning to late afternoon) or night-time hours.

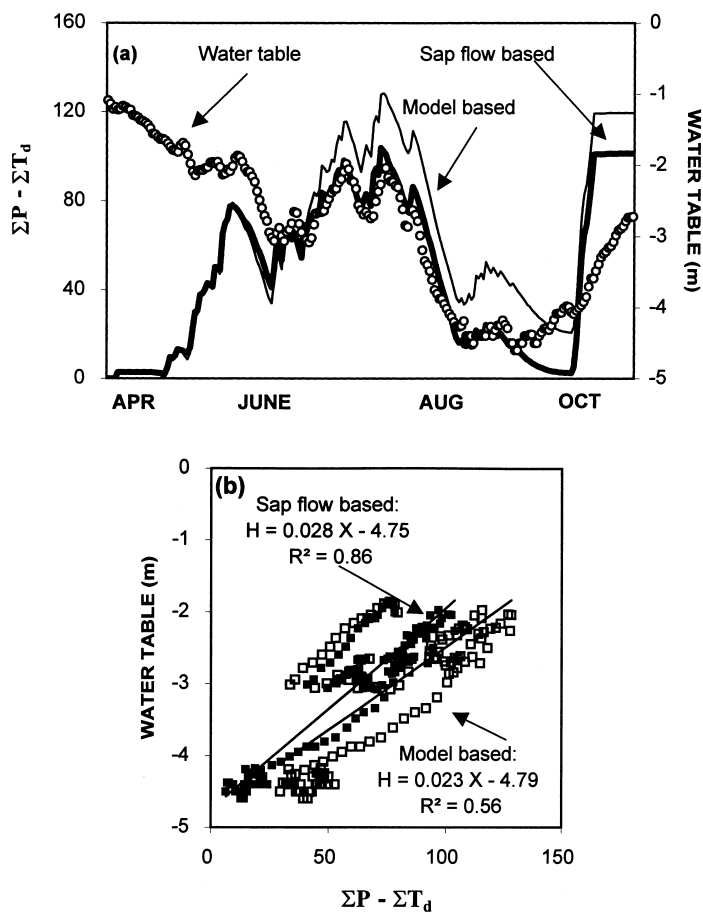


Fig. 9. (a) Seasonal course of the measured groundwater table level (H) (dotted heavy line) and of the calculated difference between cumulative precipitation ( $\Sigma P$ ) and cumulative actual transpiration ( $\Sigma T_d$ ), either measured by the sap flow method or simulated by the WAVE model. (b) Relation between ( $\Sigma P - \Sigma T_d$ ) and groundwater table level for a period with almost fully developed canopy foliage. Black squares: based on sap flow measurements, open squares: based on model.

## 5. Conclusions

This study reported reliable data on the stand transpiration of nearly mature poplar stands, namely, 320 mm for the growing season of 1997, with a daily average of 1.9 mm and a maximum of 5 mm. Furthermore, this study illustrated that the WAVE model, which simulates the water balance of a forest stand, showed good agreement with the measured transpiration, but further validation and testing are required.

## Acknowledgements

The Commission of the European Communities supported this research through the Directorate-Ge-

neral for Agriculture, contract AIR3-CT94-1753, as well as the Prime Minister's Office – Federal Office for Scientific, Technical and Cultural Affairs, contract CG/DD/05. The technical help of T. Brichau (IBW), as well as F. Kockelbergh (UIA), is greatly appreciated. We thank D.A. Sampson (UIA) for language editing.

## References

- Anonymous, 1996. Country reports of the XX session of the International Poplar Commission. Budapest, Hungary.
- Anselmi, N., 1982. Influence of attacks of *Marssonina brunnea* on the transpiration of poplar leaves. FAO/IPC meeting, XXII session, Working group on diseases. Casale Monferrato, Italy.
- Black, T.A., den Hartog, G., Neumann, H.H., Blanken, P.D., Yang, P.C., Russell, C., Nestic, Z., Lee, X., Chen, S.G., Staebler, R.,

- Novak, M.D., 1996. Annual cycles of water vapour and CO<sub>2</sub> fluxes in and above a boreal aspen forest. *Global Change Biology* 2, 219–229.
- Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J. Hydrol.* 55, 3–23.
- Cermak, J., Kucera, J., 1987. Transpiration of fully grown trees and stands of spruce (*Picea abies*(L.) Karst.) estimated by the tree-trunk heat balance method. In: Swanson, R.H., Bernier, P.Y., Woodward, P.D. (Eds.), *Proc. For. Hydrol. and Watershed Measurements*, Vancouver, Canada Aug. 1987, Publ. No. 167, IAHS-AISH, Wallingford, UK, pp. 311–317.
- Cermak, J., Kucera, J., 1990. Scaling up transpiration data between trees, stands and watersheds. *Silva Carelica* 15, 101–120.
- Cermak, J., Nadezhdina, N., 1998. Sapwood as the scaling parameter — defining according to xylem water content or radial pattern of sap flow? *Ann. Sci. For.* 55, 509–521.
- Cermak, J., Nadezhdina, N., Raschi, A., Tognetti, R., 1997. Transpiration of *Quercus pubescens* and *Quercus cerris* stands in Tuscany. Rep. Institute of Forest Ecology, Mendel's University of Agriculture and Forestry, Brno, Czech Republic, Project EC: RESMEDES; ENV4/CT95/0094, December 1997.
- Cermak, J., Riguzzi, F., Ceulemans, R., 1998. Scaling up from the individual tree to the stand level in Scots pine. I. Needle distribution, overall crown and root geometry. *An. Sci. For.* 55, 63–88.
- Dupriez, G.L., Sneyers, R., 1979. Les nouvelles cartes pluviométriques de la Belgique. Institut Royal Météorologique de Belgique, Publications, série A, No. 103.
- Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. Simulation of field water use and crop yield. *Simulation Monographs*, PUDOC, Wageningen, The Netherlands, pp. 189.
- Gardner, W., 1958. Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. *Soil Sci.* 85, 228–232.
- Gellens-Meulenberghs, F., Gellens, D., 1992. L'évapotranspiration potentielle en Belgique: variabilité spatiale et temporelle. Institut Royal Météorologique de Belgique, publications, série A, No. 130.
- Hall, R.L., Allen, S.J., 1997. Water use of poplar clones as short-rotation coppice at two sites in the United Kingdom. In: Bullard, M.J., Ellis, R.G., Heath, M.C., Knight, J.D., Lainsbury, M.A., Parker, S.R. (Eds.), *Biomass and Bioenergy Crops*. Association of Applied Biologists, Wellesbourne, Warwick, pp. 163–172.
- Hall, R.L., Allen, S.J., Rosier, P.T., Hopkins, R., 1998. Transpiration from coppiced poplar and willow measured using sap-flow methods. *Agric. For. Meteorology*, 90 (4).
- Hall, R.L., Roberts, J.M., 1990. Hydrological aspects of new broad-leaf plantations. *SEESOIL* 6, 2–38.
- Hansen, E.A., 1988. Irrigating short rotation intensive culture hybrid poplars. *Biomass* 16, 237–250.
- Harding, R.J., Hall, R.L., Neal, C., Roberts, J.M., Rosier, P.T.W., Kinniburgh, D.G., 1992. Hydrological impacts of broadleaf woodlands: implications for water use and water quality. Project report 115/03/ST, National Rivers Authority, NRA Project Reports (Severn Trent Region), Bristol.
- Hess, T.M., 1995. Potential evapotranspiration program for automatic weather stations. Silsoe College, Cranfield University, Silsoe, Bedford, UK.
- Hinckley, T.M., Brooks, J.R., Cermak, J., Ceulemans, R., Kucera, J., Meinzer, F.C., Roberts, D.A., 1994. Water flux in a hybrid poplar stand. *Tree Physiol.* 14, 1005–1018.
- Hubrechts, L., Van de Moortel, R., Feyen, J., 1997. Berekening van de bodemwaterbalans onder bos voor de proefvlakken van het 'Bosbodemeetnet Vlaanderen' (periode: 1990–1995). Internal publication No. 47, Institute for Land and Water Management, Catholic University of Leuven. (In Dutch).
- Liu, Z., Zheng, S., Zhang, D., 1988. A study on the relationship between water supply and growth in poplar plantation. FAO/IPC meeting, XXVIII session, Beijing, P. Rep. of China.
- Liu, Z., Dickmann, D.I., 1992. Responses of two hybrid *Populus* clones to flooding, drought and nitrogen availability. II. Gas exchange and water relations. *Canad. J. Botany* 71, 927–938.
- Monteith, J.L., 1965. Evaporation and the environment. In: *The State and Movement of Water in Living Organisms*. XIX Symp. Society for Experimental Biology, Swansea, Cambridge University Press, pp. 205–234.
- Nadezhdina, N., Cermak, J., 1998. The method and instrumentation for measurement of transpiration flow in plants (in Czech). Patent pending (PV – 1587 – 98). (US Patent and Trademark Rec. 69055, 1997).
- Richards, L.A., 1931. Capillary conduction of liquid through porous medium. *Physics* 1, 318–333.
- Roberts, J.M., 1983. Forest transpiration: a conservative hydrological process. *J. Hydrol.* 66, 133–141.
- Roberts, J.M., Rosier, P.T.W., 1994. Comparative estimates of transpiration of ash and beech forests at a chalk site in southern Britain. *J. Hydrol.* 162, 229–245.
- Valadon, A., Diot, F., 1996. Impact biologique de peuplements naturels et artificiels de peupliers sur le milieu: une approche bibliographique. Cemagref, Division Ressources Génétiques et Plants Forestiers, Nogent-sur-Vernisson, p. 49.
- Vanclooster, M., Viaene, P., Diels, J., Christiaens, K., 1994. WAVE: a mathematical model for simulating water and agrochemicals in the soil and vadose environment, Reference and user's manual. Institute for Land and Water Management, Catholic University of Leuven.
- van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of soil. *Soil Sci. Soc. Am. J.* 44, 892–898.
- van Genuchten, M.Th., Nielsen, D.R., 1985. On describing and predicting the hydraulic properties of unsaturated soils. *An. Geophysicae* 3, 615–628.
- Van Slycken, J., Vereecken, H., 1990. Water supply from the groundwater table and the growth of poplar: a case study. *Agric. For. Meteorol.* 50, 65–74.
- Vereecken, H., Maes, J., Feyen, J., 1990. Estimating unsaturated hydraulic conductivity from easily measured soil properties. *Soil Sci.* 149, 1–12.